RF BREAKDOWN AND FIELD EMISSION MEASUREMENT AT 470 MHZ

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ABSTRACT

Experimental results of rf breakdown at 470 MHz and field emission measurement with copper, titanium, niobium and SiO_2 coated copper are presented. The results show that the SiO_2 thin films (400 - 1000 nm) can greatly reduce field emission.

INTRODUCTION

High accelerating gradients are required by future demands such as TeV electron linear collider and acceleration of very short life time particles. RF breakdown and field emission are major factors which impose the limits on the maximum field and affect the operation of high gradient accelerators. In this paper the experimental results of the research on increasing rf breakdown and reducing field emission are reported.

PRINCIPLE OF MEASUREMENT

The test setup shown in Figure 1 has been introduced elsewhere[1]. The maximum electric field in the cavity was determined by two methods: power loss and x-ray spectrum. The power loss method determines the maximum electric field by the expression:

$$E_{max,exp} = E_{max,theo}\left[\frac{Q_{exp}P_{exp}}{Q_{theo}P_{theo}}\right]^{1/2} \qquad (1)$$

where $E_{max,theo}$, Q_{theo} and P_{theo} are the theoretical maximum electric field, Q factor and corresponding dissipated power as calculated by SUPERFISH, and Q_{exp} and P_{exp} are the experimental values.

The high energy end of the x-ray spectrum corresponds to the amplitude of the rf voltage in the gap. The maximum electric field can be determined by dividing the voltage amplitude with gap length. The fields measured by this method and the rf power measurement are used to check each other. The integrated intensity of the x-rays between the energy eV_0 and eV can be used to determine the current of the field emitted electrons by the following expression[2]:

$$I_{int} = CZ\frac{\Omega}{4\pi}(V_0^{\alpha+1} - \frac{1+\alpha}{\alpha}V_0^{\alpha}V + \frac{1}{\alpha}V^{\alpha+1})\frac{2}{\pi}a\bar{i}t \qquad (2)$$

where C is a constant, Z is atomic number of the electrode material, Ω is the solid angle from the point radiation source to the detector, α is a numerical variable which is close to 1, a is $\arcsin(V/V_0)$, $\bar{i}$ is the field emitted current averaged over the time when the rf voltage drops from the maximum V_0 to a chosen value V, t is the life time of the measurement and eV_0 is high energy end of the x-ray spectrum. I_{int} can be obtained by calculating the area between the high energy end and the chosen energy eV in the real x-ray intensity spectrum taken by the detector.

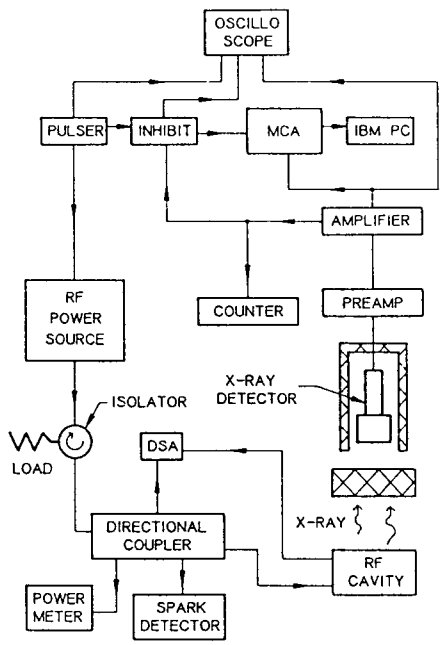

Fig. 1 RF and x-ray measurement system.

EXPERIMENTAL RESULTS

The rf breakdown field of metal electrodes is defined as the field level at which the rate of the anomalous reflected signals exceeds 1 per 100000 pulses. At such electric field levels the cavity can still be operated normally. The destructive breakdown field level can be 10-20 MV/m higher than this definition. The breakdown fields are 156 MV/m for copper electrodes, 154 MV/m for niobium electrodes and 155 MV/m for titanium electrodes at pulse length of 11 μs and repetition rate of 250 pulses per second. These breakdown fields are about 7.5 times Kilpatrick

limit. With pulse length of 9 μs and repetition rate of 50 pulses per second, the breakdown field for niobium electrode is 187 MV/m which is about 9 times the Kipatrick limit.

The breakdown fields versus various pulse lengths are plotted in Figure 2 and 3. The breakdown fields of copper do not change when the pulse lengths change from 9 μs to 13 μs. For pulse lengths longer than 13 μs the breakdown fields of copper decrease with increase of pulse lengths. The breakdown fields of niobium do not decrease up to 32 μs, then decrease slightly with increase of pulse lengths. When repetition rates are less than 200 pulses per second the breakdown fields of both copper and niobium do not depend on the repetition rate. At repetition rate of 250 pulses per second the breakdown fields of copper and niobium decrease slightly.

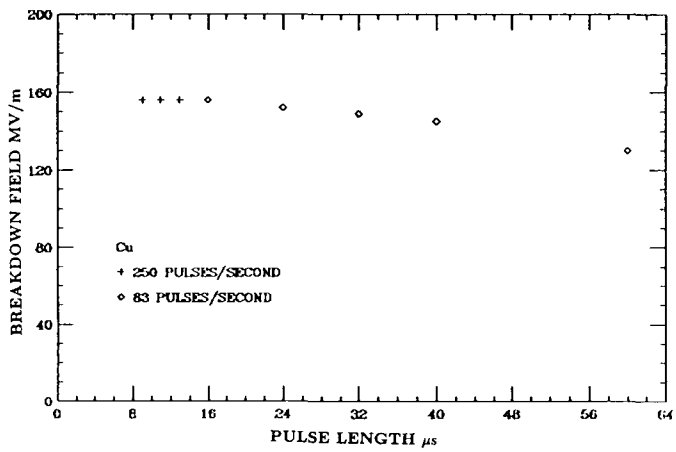

Fig. 2 Breakdown field versus pulse length (Cu).

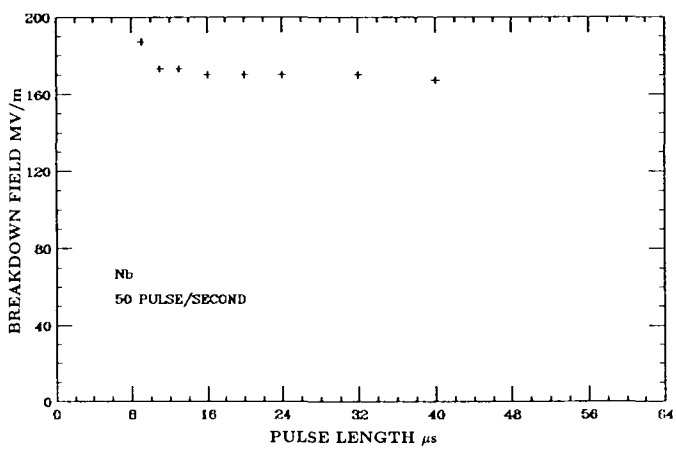

Fig. 3 Breakdown field versus pulse length (Nb).

The rf breakdown field of SiO_2 coated copper is defined as the field level at which the first drastic increase of the anomalous reflected signals occurs. This field level may be lower than the intrinsic breakdown field level of defect-free SiO_2. The reason for this definition is that after this first breakdown the field emission mainly comes from the pure copper, therefore it is unable to determine the real cause of the further breakdown. The results of breakdown field are plotted in Figure 4. The macroscopic breakdown fields vary from 96 MV/m to 156 MV/m. The sample CS6002 was tested up to field of 156 MV/m without breakdown, so the breakdown field of sample CS6002 may be higher than 156 MV/m. However, the anomalous reflected signals existed at high field and did not decrease with increase of the time. Three pairs of samples were first tested up to 80-100 MV/m (below their breakdown field), then the cavity was opened, and the sample surfaces were visually checked to ensure there was no breakdown happened. Afterwards these samples were tested again up to breakdown. One pair of samples were kept in ordinary atmosphere for seven months after such a visual check and tested again. The sample showed good repeatability until the breakdown occurred at 102 MV/m.

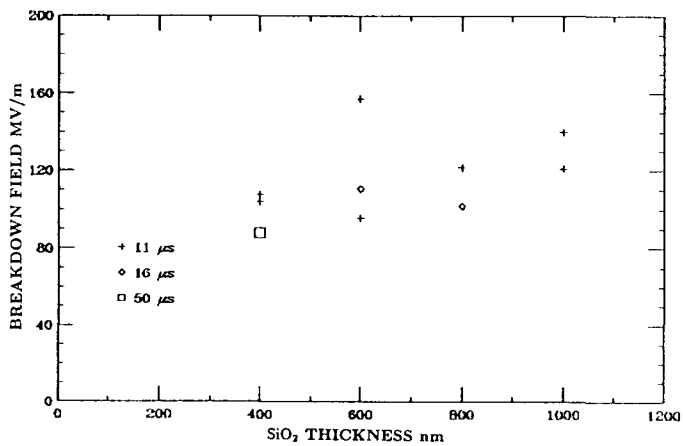

Fig. 4 Breakdown field of SiO_2 coated copper.

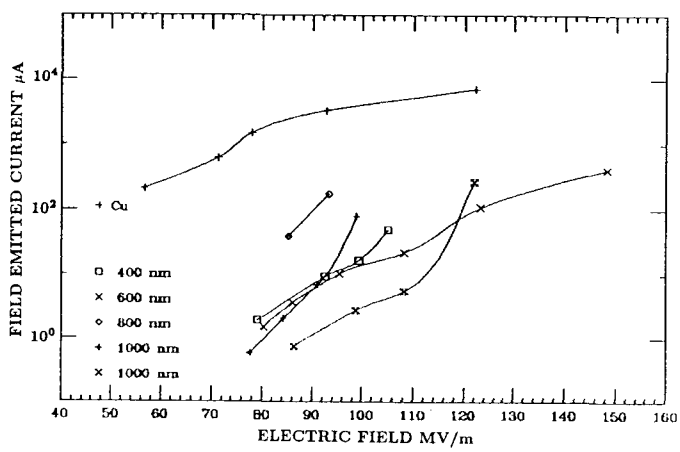

Fig. 5 Field emission current.

The field emission currents at various field levels are plotted in Figure 5. The data show that the field emission

are greatly reduced by the SiO_2 coating: the field emission from all SiO_2 coated samples are lower than that from pure copper, niobium and titanium samples. After breakdown the field emission increased drastically. The field emission of sample CS4002 at low field level (74 MV/m) was measured after first destructive breakdown at 110 MV/m which generated only one breakdown spot. The emission was at the same level as that of pure copper.

DISCUSSION

Effect of Pulse Length on RF Breakdown Field

According to dc experimental results with short pulses (5 ns - 4 μs) and the explosive emission model [3], The following relation exists:

$$j^2 t_1 = a \frac{c\delta}{d\rho/dT} \qquad (3)$$

where j is the current density, a is a material related constant, c is the specific heat, δ is the density, ρ is the resistivity, $d\rho/dT$ is the thermal coefficient of the resistivity and $\rho = d\rho/dT \times T$ is assumed. Expression 3 can not be applied directly to rf pulse. It hase been shown[2] that at 470 Mhz, an rf pulse can be simulated by a dc pulse with the same amplitude and a pulse length equivalent to 1/18 of the rf pulse length as far as the thermal effect concerned. This dc simulating pulse can be used in expression 3 to calculate the ratio of the breakdown fields at different pulse lengths by the following equation[2]:

$$\frac{E_2^4 exp[-2\frac{68.3\phi^{1.5}}{\beta E_2}]}{E_1^4 exp[-2\frac{68.3\phi^{1.5}}{\beta E_1}]} = \frac{\tau_1}{\tau_2}(dc) = \frac{\tau_1}{\tau_2}(rf) \qquad (4)$$

where E is breakdown field, β is the field enhancement factor, ϕ is the work function and the τ is the duration of the pulse which is the pulse length minus filling time. The experimental value of β is 237 for sample Cu03, τ_1 and τ_2 are 57.7 and 13.7 μs, E_1 and E_2 are 130 and 156 MV/m. By using these data, the left side of the equation 6.13 gives a value of 4.20, which is in agreement with the value of 4.21 of the right side given by τ_1/τ_2.

Reduction of Field Emission

The field emission from the SiO_2 coated copper is much lower than that from pure copper. This fact does not support the non-metallic emission model[4] which has been used to explain the rf breakdown. This dc theory predicts that the dc breakdown is initiated in the insulating impurities embeded on the surface of the metel electrods. The field enhancement in dielectrics is due to the movement or accumulation of holes or positive charges produced by hot electrons and strongly depends on the thickness of the dielectrics. The mobility of the holes in SiO_2 is only 2×10^{-5} cm^2V^{-1} in the field range $100 \sim 500$ MV/m at room temperature [5]. In a 470 MHz rf field, since the polarity of the field changes in about every nano-second, the holes are nearly immobile. Therefore the above mentioned therories may not be applicable to the rf field.

There are several mechanisms which can reduce field emisson by the SiO_2 coating: the low average field, the trapping and scattering of the electrons in the SiO_2.

Possible Cause of Breakdown of SiO_2

It has been shown[2] that heat induced by dielectric loss might not be a cause for the breakdown of the silicon dioxide in our test.

There are a lot of defects in evaporated silicon dioxide films and a lot of irregularities on the surface of the copper. The anomalous increase of field emission at the field prior to the breakdown field suggests that the breakdowns are likely to be related to the development of defects and local field enhancement. The SEM results also suggest that topography of the sample surface played an important role. On the top of the polishing mark or a microprotrusion there are several possible mechanisms which can increase the field emission, and therefore the local heating. First the local field is geometrically enhanced. Second, the SiO_2 films in such regions may have more microcracks and weak points than in smooth areas. Third, due to the local heating, the stress on the SiO_2 film in these areas is not uniform and can create more microcracks which can increase the field emission, and therefore local heating. Such feedback process may finally result in the decomposing of the SiO_2 and the evaporation of the irregularities which blow out the silicon dioxide film in that region.

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REFERENCES

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1. D. Sun, P. Datte, W. W. MacKay and F. R. Huson, "RF Breakdown Test Of SiO_2 Coated Copper Electrodes," Proceedings of the 1991 Particle Accelerator Conference, San Francisco, CA, 1991, pp. 736.
2. D. Sun, "Electrical Breakdown and Field Emission in RF Cavities" Thesis, Texas A&M University, 1992.
3. S. P. Bugaev, et al., "Explosive Emission of Electrons," Sov. Phys.-Usp., Vol. 18, No. 1, pp. 51-61, 1975.
4. R. V. Latham, "Prebreakdown Electron Emission" Proceedings of the Tenth International Symposium on Discharges and Electrical Insulation in Vacuum, pp. 3, 1982.
5. R. C. Hughes, "Hot Electrons In SiO_2," Physical Review Letters, Vol 35, No. 7, pp. 449, 1975.